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<b>13. ABSTRACT (Maximum 200 words)</b> <p>The combustion group in Talbot Laboratory at the University of Illinois (J.Buckmaster AAE, M.Short TAM, D.S.Stewart TAM. T.L.Jackson TAM (adjunct)) took the opportunity presented by the First Joint Meeting of the U.S. Sections of the Combustion Institute, held at the George Washington University, Washington DC. March 14-17. 1999, to further the visibility of the group. The P1 was a coauthor on the following papers presented at that meeting, printed in the book of abstracts (no ISBN number)</p> <ul style="list-style-type: none"> <li>(i) 'Why do pg candle-flames oscillate' by J.Buckmaster and Vi Zliaug.</li> <li>(ii) 'Non-premixed periodic flames relevant to propellant combustion' by T. L.Jackson and J.Buckmnaster.</li> <li>(iii) 'The effects of time-periodic shear on a diffusion flame anchored to a propellant by J .Buckinaster and T.L.Jackson.</li> <li>(iv) 'Cellular instabilities, sub-limit structures and edge- flames in premixed counterflows' by J.Buckmaster and M.Short. All of this work has been reported elsewhere as full length papers.</li> </ul>			
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## 1 Objectives

This research is concerned with theoretical studies of combustion and related flow problems that are relevant to the Air Force mission. Topics examined include premixed edge-flames, heterogeneous propellant flame modeling, rotational flows interior to solid rocket chambers, and oscillating non-premixed edge-flames.

## 2 Personnel

Faculty: John Buckmaster, PI

Post-doctoral students: Abdelkarim Hegab, M.Chen

PhD student: Yi Zhang

MS student J.Chenoweth worked in the program, supported by ASSERT funds.

## 3 Status of effort

**1** The combustion group in Talbot Laboratory at the University of Illinois (J.Buckmaster AAE, M.Short TAM, D.S.Stewart TAM, T.L.Jackson TAM (adjunct)) took the opportunity presented by the First Joint Meeting of the U.S. Sections of the Combustion Institute, held at the George Washington University, Washington DC, March 14-17, 1999, to further the visibility of the group. The PI was a coauthor on the following papers presented at that meeting, printed in the book of abstracts (no ISBN number):

- (i) 'Why do  $\mu g$  candle-flames oscillate' by J.Buckmaster and Yi Zhang.
- (ii) 'Non-premixed periodic flames relevant to propellant combustion' by T.L.Jackson and J.Buckmaster.
- (iii) 'The effects of time-periodic shear on a diffusion flame anchored to a propellant' by J.Buckmaster and T.L.Jackson.
- (iv) 'Cellular instabilities, sub-limit structures and edge-flames in premixed counterflows' by J.Buckmaster and M.Short.

All of this work has been reported elsewhere as full length papers.

**2** Two papers were presented at the 17th International Colloquium on the Dynamics of Explosions and Reactive Systems, July 25-30, 1999, Heidelberg, Germany. See **9,13**.

**3** The PI presented an invited plenary lecture at ANZIAM '99, the 35th Australian Applied Mathematics Conference, Mollymook, New South Wales, Australia, 7-11 February 1999. No AFOSR funds were spent for this trip. The subject of the lecture was edge-flames. A talk was also given at the concurrent meeting in honor of Professor Brian F. Gray, also held at Mollymook, the subject being propellant flames.

**4** A summary of contract work was presented at the 1999 ARO and AFOSR Contractor's Meeting in Chemical Propulsion, held in Bar Harbor, Maine, June 13-16.

**5** The paper 'An elementary discussion of propellant flame geometry' by J.Buckmaster, T.L. Jackson, and J.Yao was published: *Combustion & Flame* **117** 541-552 (1999). Its abstract reads: *We examine the geometry of diffusion flames generated by the burning of a heterogeneous solid propellant, using a simple model designed to provide qualitative insights. In the fast chemistry limit a strategy is used which has its roots in Burke and Schumann's 1928 study of diffusion flames, albeit with different boundary conditions. This shows that the stoichiometric level surface (SLS) intersects the propellant surface at a point displaced from the fuel/oxidizer interface, and the variations of this*

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displacement with Peclet number are discussed. We show that for model sandwich propellants, or their axisymmetric counterpart, the geometry of the SLS when the core is oxidizer is quite different from the geometry of the SLS when the core is fuel. Also, it is much easier to quench the flame on an oxidizer core, than it is to quench the flame on a fuel core. When finite chemistry effects are accounted for, the flame only occupies a portion of the SLS, and there is a leading edge structure in which premixing plays a role. Enhancement of the burning rate due to premixing is identified, but a well-defined tribrachial structure is not observed. We show how a sharp reduction in pressure can lead to a detachment of the flame from the SLS, with subsequent quenching as it is swept downstream.

6 A paper that is related in some ways to 5 was published in *Combustion & Flame* 120 211-221 2000. Its title is 'The effects of a time-periodic shear on a diffusion flame anchored to a propellant' by J.Buckmaster, and T.L.Jackson. Its abstract reads:

We examine a single diffusion flame anchored to 1/4-spaces of solid fuel and oxidizer, a configuration relevant to the combustion of heterogeneous solid propellants. A time-periodic shear flow is applied, to model the shear that can be generated by the interaction of acoustic waves and the rotational base flow in a rocket chamber. The response of the flame to this shear, the heat flux to the surface etc., are calculated numerically. Significant enhancement of the maximum temperature and the time averaged total heat flux to the surface are found. These enhancements are essentially maximized at zero frequency, and at low frequencies the response depends critically on the instantaneous direction of the shear.

7 Another propellant study was published in the *Journal of Propulsion & Power* vol.16, pp. 498-504, 2000. Its title is 'Non-premixed periodic flames supported by heterogeneous propellants' by T.L.Jackson, and J.Buckmaster. Its abstract reads:

This is one of a sequence of elementary flame studies designed to provide an understanding of the complex combustion field that is generated by burning a heterogeneous solid propellant of the kind used in high-performance rockets. We consider a propellant whose surface is one-dimensional periodic, generating a two-dimensional combustion field. Two important parameters are the Peclet number  $Pe$  and the solid-phase stoichiometric coefficient  $\beta$ . We show that for  $\beta = 7$ , a representative value, there are essentially two flame configurations: For small Peclet numbers, mixing between the surface and the flame is sufficient to generate a continuous and near-uniform deflagration; on the other hand, for Peclet numbers of order 10 or so, each period contains a pair of button-like premixed flames centered over the fuel so that there are significant 'holes' in the combustion field over the oxidizer. Diffusion-flame structures that are part of the combustion field play no role in generating the heat that is conducted back to the propellant surface. Most of our calculations assume that both Lewis numbers are equal to 1 and the solutions are steady, but time-periodic oscillating solutions are obtained for sufficiently large values of Lewis number.

8 Our strategy in modeling propellant flames has been to add incremental complexity. Papers 5-7 do not incorporate the full Navier-Stokes equations, for example. But a study which does so was published in *Journal of Propulsion & Power*. Its title is 'Periodic propellant flames and fluid-mechanical effects' by T.L.Jackson, and J.Buckmaster. Its abstract reads:

We construct the combustion field generated by a periodic reactant supply that models the supply from a heterogeneous propellant. A full accounting of the fluid mechanics is incorporated. However, solutions differ little from those generated assuming a uniform mass flux (the constant density model). On the other hand, allowing for temperature dependent transport (power law or Sutherland's law) strongly affects the reaction rate and the heat flux to the propellant surface. The effects of

*nonuniform mass flux at the propellant surface are also discussed.*

9 We have carried out 3D flame calculations for flames supported by 2D heterogeneous propellant surfaces. A talk on this work was presented at the 17th International Colloquium on the Dynamics of Explosions and Reactive Systems, July 25-30, 1999, Heidelberg, Germany, and an abbreviated report appears in the proceedings of this meeting (cd only, ISBN 3-932217-01-2). Its title is 'Three-dimensional SRM propellant flames' by T.L.Jackson, and J.Buckmaster. Its abstract is:

*This is one of a sequence of elementary flame studies designed to provide an understanding of the complex combustion field that is generated by burning a heterogeneous solid propellant of the kind used in high performance rockets. Here, for the first time, we examine periodic three-dimensional flames supported by a periodic array of spherical AP particles imbedded in a fuel binder. A strategy for dealing with a wide range of AP particle sizes is proposed, and some preliminary calculations of flame configurations are presented.*

10 The paper 'Response of propellant flames to unsteady flows and related questions' by J.Buckmaster and T.L.Jackson, AIAA paper 99-0323, was presented at the 37th AIAA Aerospace Sciences Meeting in Reno, Nevada, January 1999. This is a compilation of papers 5-7, presented at this meeting to further expose our work to the mainstream propellant community.

11 We engaged in a study of rocket motor flows. The paper 'The generation of axial vorticity in solid-propellant rocket-motor flows' by S.Balachandar, J.Buckmaster, and M.Short was published in the *Journal of Fluid Mechanics* 429 283-305 2001. Its abstract is:

*We examine small deviations from axial symmetry in a solid-propellant rocket motor, and describe a 'bath-tub-vortex' effect, in which substantial axial vorticity is generated in a neighborhood of the chamber center-line. The unperturbed flow field is essentially inviscid at modest Reynolds numbers, even at the chamber walls, as has long been known, but the inviscid perturbed flow is singular at the center-line, and viscous terms are required to regularize it. We examine perturbations so small that a linear analysis is valid everywhere ( $\epsilon Re$  small, where  $\epsilon$  is a measure of the perturbation amplitude and  $Re$  is a Reynolds number); and larger perturbations in which a nonlinear patch is created near the center-line of radius  $O(\sqrt{\epsilon})$ . Our results provide an explanation of swirl experimentally observed by others, and a cautionary note for those concerned with numerical simulations of these flows, whether laminar or turbulent.*

This work was reported at the annual Division of Fluid Dynamics meeting of the American Physical Society, November 1998, Philadelphia, PA.

13 We carried out 3D flame calculations for flames supported by 2D heterogeneous propellant surfaces. We presented a paper at the 28th International Symposium on Combustion in August 2000, and it was published in the Proceedings. (These Proceedings are now given the same status as Journal publications by the citation authorities, and have been renamed to reflect this fact. Thus the Proceedings of the 28th Symposium were published with the title 'Proceedings of the Combustion Institute, vol. 28 pp \* 2000'.) Its title is '3D flames supported by heterogeneous propellants' by T.L.Jackson, J.Buckmaster, J.Hoeflinger. Its abstract reads:

*We examine a surface which mimics that of a heterogeneous propellant and through which passes distributed fluxes of oxidizer and fuel. The three-dimensional flames supported by these fluxes are calculated using a simple model. An elementary propellant packing model defines a variety of flux distributions according to the level of the slice through the propellant which defines the surface, and the effect of the different distributions on the combustion field and on the heat flux to the surface is discussed. An important geometric effect is identified. The more likely that arbitrary surface area fractions contain both AP and binder fluxes, the greater will be the total heat flux to the surface*

from the AP/binder flames. The likelihood, and therefore the heat flux, is maximized for fuel-rich slices.

The acceptance rate for all contributions to the 28th Symposium was 45%.

**14** In order to properly model a heterogenous propellant, it is necessary to use a packing algorithm which will define a propellant morphology. The following paper on this subject was published in the *AIAA Journal*. Title 'The random packing of heterogeneous propellants' by G.M.Knott, T.L.Jackson, J.Buckmaster. Its abstract reads:

*A random packing algorithm is implemented in order to numerically construct models of heterogeneous propellants. These models consist of random distributions of spheres in a periodic cube. The spheres can have various sizes, randomly assigned if desired. Packing fractions are calculated for a bimodal model (spheres of two different sizes) and compare well with old experimental data for steel shot. Slices through the cube define surfaces which represent propellant surfaces, and the stoichiometry of these surfaces is a stochastic variable. Several realizations of the propellant cube are constructed and variations in surface stoichiometry are examined using histograms and Fourier series. A sample flame calculation is presented, solved using data defined by a single surface realization.*

**15** A summary of our work on heterogeneous propellants was presented as *AIAA paper 2000-0306* at the 38th Aerospace Sciences Meeting, Reno, NV, Jan. 2000.

**16** The paper 'Random propellant packs and the flames they support' by S.Kochevets, J.Buckmaster, T.L.Jackson was presented as *AIAA paper 2000-3461* at the 36th Joint Propulsion Conference, Huntsville, AL, July 2000. Its abstract is:

*This work extends our earlier work on packing algorithms, a strategy for defining and constructing a model heterogeneous propellant (Knott, Jackson, and Buckmaster), by including experimental AP size data. Two strategies for defining a pack using the experimental data are identified and discussed. For each strategy, packing densities are computed and compared with known experimental data. A sample flame calculation is also presented, solved using data defined by a single packing realization.*

**17** The paper 'The burning of periodic sandwich propellants' by A.Hegab, T.L.Jackson, J.Buckmaster, D.S.Stewart was presented as *AIAA paper 2000-3459* at the 36th Joint Propulsion Conference, Huntsville, AL, July 2000. Its abstract is:

*We develop a mathematical model which describes the unsteady regression rate determined by simultaneously solving the combustion field in the gas-phase and the thermal field in the solid phase, with appropriate jump conditions across the gas/solid interface. The model takes into account the AP decomposition flame, reaction between the AP products and the binder gases, properties of the AP and binder, variable gas-phase transport properties, and the unsteady non-planar regressing surface. A Hamilton-Jacobi equation is used that governs the propagation of the unsteady regressing surface. Although the formulation is general, we consider here only the periodic sandwich geometry. Numerical studies show that the surface evolves into a quasi-steady propagating front. The regression rate is calculated as a function of pressure, fuel matrix thickness, AP particle size, and gas-phase Peclet and Damköhler numbers. The gas-phase flame structure as well as the surface shape are also shown.*

**18** The following paper was published in *Journal of Propulsion & Power* **17**(4) 883-891 2001. It is the final version of **16**. Its title is 'Random packs and their use in the modeling of heterogeneous solid propellant combustion' by S.Kochevets, J.Buckmaster, T.L.Jackson, A.Hegab. Its abstract reads:

*It is shown that random packs of spheres of various sizes can be constructed that model ammonium-perchlorate-in-binder propellants in the sense that both the size distributions and the packing fractions of industrial propellant packs can be matched. Strategies for dealing with fractional numbers of large particles are addressed, as are strategies for dealing with a large number of very fine particles (fine powder). Fine powder is necessary in a three-dimensional pack to achieve the required stoichiometric ratio of ammonium perchlorate to fuel binder, but is not necessary in a two-dimensional (disk) pack. Some preliminary calculations of the two-dimensional combustion field supported by a disk pack are presented, in which full coupling between the gas phase, the condensed phase, and the retreating nonplanar propellant surface is accounted for.*

One of the reviewers of this paper identified himself as M. Beckstead, one of the leaders in the propellant community. In his review he writes: "This is a very important manuscript and it should be published as intact as possible".

**19** Another propellant study was published in the *AIAA Journal*. Its title is 'Heterogeneous propellant combustion' by T.L.Jackson, and J.Buckmaster. Its abstract reads:

*In earlier work it has been shown that spheres of various sizes can be randomly packed to simulate the morphology of AP/binder heterogeneous propellants. Here we formulate a model in which propellants defined in this way can be burnt, allowing for complete coupling between the gas-phase physics, the condensed-phase physics, and the unsteady nonuniform regression of the propellant surface. The gas-phase kinetics is represented by a 2-step model with parameters fitted to experimental data for the one-dimensional combustion of pure AP, and the one-dimensional combustion of a fine-AP/binder blend. In discussing the pure AP fits, the issue of intrinsic instabilities arises, and these are explored using nonlinear DNS and a numerical linear-stability strategy. Results for two-dimensional heterogeneous burning show that surface regions where the AP and binder can mix regress more rapidly than those dominated by AP; local extinction can occur where the binder dominates. Time variations in the integrated flux-based equivalence ratio are shown to be large. Variations in the average burning rate with pressure are consistent with the (three-dimensional) experimental record.*

The following remarks were made by the four reviewers of this paper: "This paper represents a significant piece of work, a major advance in the modeling of AP-composite propellant combustion (probably the most significant advance in the last 40 years) and should definitely be published."; "The ability to simulate even a 2-D random-pack combustion field is quite striking, and I wholeheartedly endorse publication."; "This is an important study by authors who have been systematically improving the state of the art of propellant combustion."; "I believe this paper must be published. I also believe it will become a significant reference in the field."

**20** The paper 'Nonsteady burning of periodic sandwich propellants with complete coupling between the solid and gas phases' by A.Hegab, T.L.Jackson, J.Buckmaster, D.S.Stewart was published in *Combustion & Flame* **125** 1055-1070 2001, Its abstract is:

*We develop a mathematical model that describes the unsteady burning of a heterogeneous propellant by simultaneously solving the combustion field in the gas-phase and the thermal field in the solid phase, with appropriate jump conditions across the gas/solid interface. The model takes into account the AP decomposition flame, reaction between the AP products and the binder gases, different properties (density, conductivity) of the AP and binder, temperature-dependent, gas-phase transport properties, and the unsteady non-planar regressing surface. Propagation of the latter is described by using a level-set formulation which gives rise to a Hamilton-Jacobi equation. Numerical studies for a periodic sandwich geometry show that the surface evolves unsteadily into a steadily propagating*

front, and the effects of various parameters (pressure, stoichiometry, length scale) on the steady propagation speed are discussed. A variety of surface shapes are predicted, depending on the parameter values. It is shown that accounting for the full Navier-Stokes equations in the gas-phase yields results that differ little from those generated when an Oseen model is adopted.

We were engaged in a study of edge-flames. If one thinks of a 1D flame as an infinite flame sheet, occupying the entire plane, then an edge-flame can be thought of as a semi-infinite flame sheet, occupying half the plane, and therefore having an edge. An edge-flame propagates in a wave-like fashion with a well-defined speed and represents a fundamental flame structure that arises in a wide variety of physical circumstances.

We were the first to show that edge-flames can arise in premixed combustion and the paper (the second on this topic) 'Two-dimensional failure waves and ignition fronts in premixed combustion' by T.G.Vedarajan, J.Buckmaster, and P.Ronney was published in the Proceedings of the 27th International Symposium on Combustion, pp. 537-544, 1998. Its abstract is:

*This paper is a continuation of our work on edge-flames in premixed combustion. An edge-flame is a two-dimensional structure constructed from a one-dimensional configuration that has two stable solutions (bistable equilibrium). Edge-flames can display wavelike behavior, advancing as ignition fronts or retreating as failure waves. Here we consider two one-dimensional configurations: twin deflagrations in a straining flow generated by the counterflow of fresh streams of mixture; and a single deflagration subject to radiation losses. The edge-flames constructed from the first configuration have positive or negative speeds, according to the value of the strain rate. But our numerical solutions strongly suggest that only positive speeds (corresponding to ignition fronts) can exist for the second configuration. We show that this phenomenon can also occur in diffusion flames when the Lewis numbers are small. And we discuss the asymptotics of the one-dimensional twin deflagration configuration, an overlooked problem from the 70s.*

21 The following paper was published: *Combustion Theory and Modeling* 3 199-214 (1999). 'Cellular instabilities, sublimit structures and edge-flames in premixed counterflows' by J.Buckmaster and M.Short. Its abstract reads:

*We examine twin premixed flames in a plane counterflow and uncover, in the parameter space, a hitherto unknown domain of cellular instability. This leads us to hypothesize that for small Lewis numbers a 2D steady solution branch bifurcates from the 1D solution branch at a neutral stability point located near the strain-induced quenching point. Solutions on this 2D branch are constructed indirectly by solving an initial value problem in the edge-flame context defined by the multiple-valued bistable 1D solution. Three kinds of solution are found: a periodic array of flame-strings; a single isolated flame-string; and a pair of interacting flame-strings. These structures can exist for values of strain greater than the 1D quenching value, corresponding to sublimit solutions.*

This work was presented at Eurotherm seminar 61 "Detailed studies of combustion phenomena" which was held in October 1998 in 's Hertogenbosch, the Netherlands, and an abbreviated report appears in the proceedings, pp D33-D36 (ISBN 90-386-0810-1).

In addition it was reported at the 37th Aerospace Sciences Meeting, Reno, Nevada, January 1999, paper 99-0701, titled 'Sublimit combustion'.

22 Non-premixed edge-flames are known to oscillate under certain circumstances, the reason for which has been both uncertain and controversial. We believe that we have correctly identified the reason. This is reported in a paper which was published in *Combustion Theory & Modeling*. Its title is: 'Oscillating edge-flames' by J.Buckmaster and Yi Zhang. Its abstract is:

*It has been known for some years that when a near-limit flame spreads over a liquid pool of fuel, the*

edge of the flame can oscillate. It is also known that when a near-asphyxiated candle-flame burns at zero gravity, the edge of the (hemispherical) flame can oscillate violently prior to extinction. We propose that these oscillations are nothing more than a manifestation of the large Lewis number instability well-known in chemical reactor studies and in combustion studies, one that is exacerbated by heat losses. As evidence of this we examine an edge-flame confined within a fuel-supply boundary and an oxygen-supply boundary, anchored by a discontinuity in data at the fuel-supply boundary. We show that when the Lewis number of the fuel is 2, and the Lewis number of the oxidizer is 1, oscillations of the edge occur when the Damköhler number is reduced below a critical value. During a single oscillation period there is a short premixed propagation stage and a long diffusion stage, behavior that has been observed in flame spread experiments. Oscillations do not occur when both Lewis numbers are equal to 1.

**23** A sequel to **22** was published in the *Physics of Fluids* vol.12, pp 1592-1600, 2000. Its title is: 'More results on oscillating edge-flames' by J.Buckmaster, A.Hegab, and T.L.Jackson. Its abstract is:

We examine a simple model of a side-anchored non-premixed edge-flame in order to gain insights into the oscillations that are sometimes observed in microgravity candle burning, flame-spread over liquids, etc. Previous results describe the role played by the Lewis number of the fuel, and the Damköhler number, and here we examine both the effects of an on-edge and off-edge convective flow, and the effects of a heat sink. The on-edge flow and the heat sink tend to destabilize, the off-edge flow tends to stabilize, results consistent with our hypothesis regarding the genesis of the oscillations.

This work was also presented as *AIAA paper 2000-0847* at the 38th Aerospace Sciences Meeting, Reno, NV, Jan.2000.

**24** Interest in hydrogen combustion has increased in recent years, as its combustion products do not contribute to greenhouse warming. Hydrogen flames are subject to strong Turing instabilities, and these have a big influence on turbulent hydrogen combustion. A remarkable range of flame structures generated by the instabilities are reported in the following paper, published in *Combustion & Flame* vol.125, pp 893-905, 2001. Title 'Edge-flames and sublimit hydrogen combustion' by M.Short, J.Buckmaster, S.Kochevets. The abstract reads:

We discuss edge-flames in the context of the plane counterflow of air and nitrogen-diluted hydrogen. For sufficiently dilute hydrogen streams, strong cellular instabilities arise which affect the dynamics of the edge-flames and, in the long term, give rise to residual cellular structures. Depending on the Damköhler number, solutions are constructed corresponding to: an advancing edge trailing a smooth flame; an advancing edge trailing a stationary periodic cellular structure, a warp of flame-strings; a finite array of flame-strings which drift apart from each other at a decreasing rate; a single stationary flame-string; dual stationary flame-strings; triple stationary flame-strings. Many of these solutions are sublimit in the sense that they exist for Damköhler numbers smaller than the one-dimensional quenching value defined for the counterflow configuration. The connection of these solutions to the linear stability of the one-dimensional system is discussed, and evidence of a subcritical bifurcation is presented. Comparisons are made with experimental results obtained by Ronney.

**25** What happens to holes torn in flames by turbulence is of fundamental importance in a large number of important industrial applications. Our edge-flame studies have examined this question, and a paper was presented at the 28th International Symposium on Combustion in August, and was published in the Proceedings (publication year 2000). Its title is 'Holes in flames, flame-isolas,

their edges', by J.Buckmaster, T.L.Jackson. Its abstract is:

*We examine a simple model problem designed to provide insight into how easily a hole in a diffusion flame can close, and how easily an isolated region of burning in a mixing region (a flame-isola) can grow. With the thickness of the mixing-layer/diffusion-flame defining the characteristic length, we find that a hole of diameter  $\approx 1$  will close for all but a tiny interval of Damköhler numbers above the one-dimensional quenching value; a hole of diameter  $\approx 3$  will close for Damköhler numbers that exceed the quenching value by more than 30-40%, depending on the Lewis number; and a hole of infinite diameter will close for Damköhler numbers that exceed the quenching value by more than  $\sim 70\%$ . Even larger Damköhler numbers are required for isolas to grow, and we calculate these values for different radii. We investigate the speeds with which hole edges or isola edges advance or retreat, and provide evidence that for a shrinking hole or isola a meaningful speed can be defined that depends only on the combustion parameters and the instantaneous hole/isola radius.*

The acceptance rate for submissions in the category 'Laminar flames' to the 28th Symposium was 35%.

**26** Two papers were presented at the Eighth International Conference on Numerical Combustion held at Amelia Island, Florida, in March 2001. Their titles are:

'A numerical study of simple edge-flame models', J.Buckmaster

'Modeling combustion of rocket motors', T.L.Jackson, J.Buckmaster

**27** Two papers were presented at ICTAM 2000 (International Conference on Theoretical and Applied Mechanics) in Chicago, Illinois, in August 2000. Their titles are:

'The dynamics of edge-flames', J.Buckmaster

'Random packing of heterogeneous propellants and the flames they support', T.L.Jackson, J.Buckmaster, A.Hegab, G.Knott.

## 4 Public service

- The PI was program chair for the 17th International Colloquium on the Dynamics of Explosions and Reactive Systems, July 25-30, 1999, Heidelberg, Germany.
- The PI was co-program chair (with M.Smoode and D.S.Stewart) for the Eighth International Conference on Numerical Combustion, organized by SIAM, to be held at Amelia Island, Florida, in March 2000.
- The PI, assisted my M.Matalon, organized a prenominated session on combustion for the meeting ICTAM 2000, at the request of the conference program committee.
- The PI is a member of the Propulsion and Combustion Technical Committee of the American Institute for Aeronautics and Astronautics.
- The PI is on the editorial board of the journal *Combustion Theory and Modelling*.

## 5 Recognition

- The PI was appointed as a 'Very Important Visitor' at the Institute of Mathematics and its Application, in Minneapolis, Minnesota, for September-December 1999.

- J.Buckmaster gave an invited plenary lecture at the British Applied Mathematics Colloquium in April 2000, Its title was 'Phascinating Phlames for Neophytes'.
- In the Proceedings of the Combustion Insitute, comments to papers are published with the papers. Item 8 above received the following comment from Dr.Merrill King, who currently works at NASA Headquarters: 'My congratulations - this is the best work attacking the complexities of heterogeneous propellant combustion that I have seen in my 35 years in the business. I am truly impressed with what Buckmaster and Jackson are doing.'
- J.Buckmaster gave an invited plenary lecture at a special combustion colloquium held in Durham England in July 2001.
- He also gave an invited plenary lecture at a joint meeting of the Spanish and Mexican sections of the Combustion Institute held in Veracruz Mexico in April 2001.
- And he also gave an invited plenary lecture at a Gordon Conference on microgravity combustion held at New London, New Hampshire in July 2001.

## 6 Honors

- Senior U.S. Scientist Award (Humboldt Prize), 1985, 1986  
Buckmaster, J.  
Alexander von Humboldt Foundation, Germany
- JSPS Fellow, 1986  
Buckmaster, J.  
Japan Society for the Promotion of Science, Japan
- Fellow, American Physical Society, 1986  
Buckmaster, J.  
American Physical Society, USA
- Guggenheim Fellowship, 1990  
Buckmaster, J.  
Guggenheim Foundation, USA
- Fellow of the Institute of Physics (UK), and Chartered Physicist, 1999  
Buckmaster, J.  
The IOP is an international learned society and professional body for the advancement and dissemination of physics, pure and applied, and promotion of physics education. Its headquarters is in Bristol, England.
- Fellow of the Department of Theoretical and Applied Mechanics, University of Illinois, 1999-  
Buckmaster, J.  
This appointment recognizes the contributions to and the support of the science of mechanics by the PI. The number of such fellows is restricted to no more than 20% of the number of full time faculty within the TAM department.

- AIAA Propellants and Combustion Prize, 2002  
Buckmaster, J.  
American Institute of Aeronautics and Astronautics, USA
- University fellowship  
Yi Zhang  
University of Illinois

## 7 Other activity

J.Buckmaster is a participant in a DOE ASCI center, concerned with the numerical simulation of rocket motors, centered in the Computer Science and Engineering program of the University of Illinois, where his role is to provide guidance in the context of propellant flame physics and chemistry. The collaborative work with T.L.Jackson, a senior research scientist in the center, comes about because of this.